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Visual Comfort Evaluation in Residential Buildings: a Simulation-Based Study

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Abstract— Despite desirability of direct sunlight access in residential buildings, visual discomfort risks for these building types are less known. A simulation-based study was performed on a typical residential building with heritage value in central Copenhagen in order to evaluate its visual comfort characteristics using existing methods. Our results show that, although high relative contrast exist for view-directions not only towards window, these situations are not captured by the existing methods. A new method for quantification of a relative contrast over the 360° span of the space was thus introduced.

Index Terms—Daylighting, Gaze (View) direction, Residential buildings, Visual comfort, HDRI techniques

I. INTRODUCTION

Visual discomfort caused by daylight has been observed in extend targeting commercial buildings with a focus on office buildings. These studies have proposed several metrics to describe discomfort caused by excessive or unbalanced luminous contrast within a fixed Field of View (FOV) with respect to a office visual task-area [1], e.g. monitor screen. Task-oriented visual comfort evaluation, however, does not seem to be as relevant in residential interior spaces where the classification of a task and its position is less defined. Although several studies have explored the applicability of different daylight metrics to residential buildings [2] and daylight energy saving benefits [3], the visual comfort assessment methods in this building typology have not been addressed.

The visual comfort assessment methods are developed majorly in experimental set ups under electrical lighting with few exceptions that address this phenomenon under daylight conditions [4]. These methods rely on empirical models where subjective human response is correlated with a sophisticated relation of physical photometric quantities that represent perceived luminance contrast at the eye level. One of these models which addresses daylight-induced visual discomfort is Daylight Glare Probability (DGP) index. DGP is used to quantify the percentage probability of glare perception, developed for an office room under daylight conditions [5].

The DGP formula consists of two main components. The first component is the vertical illuminance at the eye level (E_v). This parameter shows a particular sensitivity when direct sun is the cause of visual discomfort. The second one, Glare Impact (GI) [6], is a summation of the luminance of all the glare sources weighted by their corresponding size in solid angle unit and sensitivity in the FOV measured by a Position Index (PI) function [7], and finally divided by E_v . The GI accounts for contrast-induced glare, meaning the discomfort caused by high contrast between the center area of the FOV and the surroundings. Nevertheless, its contribution to the overall result for DGP is considerably smaller than E_v . As a result, the impact of contrast on the potential visual discomfort sensation is considered only to a limited extend when using the DGP index.

In buildings with relatively small windows and thick walls, the daylight levels are low and presence of daylight and direct sunlight during the majority of the occupied hours is rare, and therefore, almost no discomfort caused by excessive glare or higher illuminance levels at the eye is detected when running the numerical simulations for the DGP index. However, high contrast between window area and the rest of the room can occur. Knowing that contrast variations even in lower luminous environments can cause discomfort [8], in order to detect these conditions in these buildings, we have developed a new method based on relative illuminance contrast. The newly developed Relative Contrast model (RC) is based on relative contrast in the FOV. We used this method for detection of potential visual contrast-induced discomfort in the chosen case study building and determination of its view-direction dependency [9, 10].

The objective of the presented study is to detect the potential visual comfort and determine its view direction dependency in a typical old apartment building in Copenhagen by using the Relative Contrast model.

II. METHODOLOGY

Photometric behavior of a selected case study was observed with numerical simulations using the lighting rendering tool, Radiance [11]. The chosen residential building for this study represents a larger range of buildings in central Copenhagen, built in period from 1850 till mid 1950s, using the same principles [12]. These buildings have masonry thick walls and relatively small windows (1 m with to 1.65 m height in living rooms). The building has five above ground stories – ground floor plus four floors. There are 8 apartments located on each floor - 6 of them with the E-W orientation, 1 facing N-S, both types consisting of a living room, bedroom and kitchen, and 1 apartment with the windows facing SW and NE and an additional bedroom.

The relative illuminance contrast in living rooms and kitchens of several apartments of the case study building was investigated. This was done using High dynamic range (HDR) rendering techniques with angular fisheye perspective view types rendered in Radiance. The illuminance contrast was calculated as a standard deviation of illuminance values on each rendered image. To be calculated, it was thus necessary to first derive the illuminance values of the images' pixels, bearing in mind that each image is a 2-dimensional transformation of 3-dimensional space with the specified angular projection algorithm. We used Evalglare tool [5] to derive the solid angle distribution of pixels, DGP and the glare sources' luminance intensity and size. The obtained data from Evalglare was used in Matlab to calculate the Relative Contrast (RC). In order to compare the view direction dependency and applicability of the DGP index components and RC, the angular fisheye images HDR images were rendered for a range of view directions with an immersive approach [13] for different room types in the selected case study. All the simulations were done for four selected points in time during the occupancy hours on equinox and solstice days – March 20, June 21, and September 22 and December 21 – at 7 a.m., 9 a.m., 4 p.m. and 6 p.m. During the simulation process, it turned out not to be possible to render the images for 21.12 at 6 p.m. due to insufficient level of daylight at this time of the shortest day in the year. The whole process is described in details in the following paragraphs. Due to space limitation, only results from the simulations for living rooms in two apartments in the buildings are presented in the paper.

A. Immersive Spatial Approach

Investigations for contrast assessment in the rooms of the case study building was done using an immersive spatial approach [13]. Instead of choosing one camera view direction for the simulation, a range of view directions were considered to render a set of images that can constitute a base for contrast analysis. For this purpose, the camera was placed in the centre of each of 4 investigated room at the height of 122 cm (the average height of a sitting persons eyes) and oriented towards 9 different directions. The rule for adjusting view directions was the same for all investigated rooms, despite their orientation – the first view direction was perpendicularly towards the window, and the following ones were clockwise rotated 40° apart.

B. Solid angle and Position index determination using Evalglare

The HDR images, were generated by use of the angular (-vta) fisheye view type [11]. The principle for fisheye projection is that the distance from the center of the image is proportional to the angle of the camera's view direction. As a result, half of the environment (in this case the room space) is projected onto a spherical image. Using the Radiance-based tool Evalglare [5], size of all pixels in solid angle values for the fisheye images were determined. Another parameter derived from Evalglare, which was further used is the Position Index (PI) parameter for all pixel points. These two parameters were then used in RC for quantifying the relative contrast of each rendered image. Within the same processing workflow in Evalglare, DGP, Ev and GI components were derived. The latter was then calculated for all cases in Matlab.

C. Image Contrast Calculation in Matlab

Sets of fisheye HDR images showing the 9 view directions of each room at each point in time were read in Matlab along with their RGB values and pixel parameters. The first step in order to assess the contrast on each of the images was to calculate the illuminance values of image pixels. For this purpose, the illuminance for each pixel was calculated based on using the RGB values (1).

$$\text{Illuminance} = 179 \cdot (0.265 \cdot R + 0.670 \cdot G + 0.065 \cdot B) \quad (1)$$

In order to account for the pixels' sizes, the calculated values of pixels' illuminances were multiplied by corresponding solid angle values. The resulting pixels illuminance values weighted by the pixels' sizes were used to calculate the contrast on each image. The relative contrast (RC) was calculated based on the standard deviation of the pixels illuminance values according to (2). This relative contrast was also calculated based on the pixels illuminance values weighted by the PI (RC_{PI}) (3).

$$RC = \frac{1}{L_m} \sqrt{\frac{1}{N} \sum (L_i \cdot \omega_i - \mu_1)^2} \quad (2)$$

$$RC_{PI} = \frac{1}{L_m} \sqrt{\frac{1}{N} \sum \left(\left(L_i \cdot \omega_i / P_{index} \right) - \mu_2 \right)^2} \quad (3)$$

Where

L_m – average luminance of the scene

L_i – luminance of the pixel

ω_i – solid angle of the pixel

P_{index} – position index of each pixel

μ_1 – mean of all value corresponding to $(L_i \cdot \omega_i)$

μ_2 – mean of all value corresponding to $(L_i \cdot \omega_i / P_{index})$

D. DGP_c : The Photometric Relation of DGP

The photometric components of the DGP, i.e. Ev and GI, were derived processing all the images. The sum of Ev and GI represents the photometric part of the DGP formula. This relation, which is called DGP_c here, includes only the photometric quantities of DGP without the weighting exponents, which are determined by the empirical modelling process in accordance with the subjective responses from the study behind the formula [5]. DGP_c allows for comparison of the results only based on photometric variations. DGP_c , Ev and GI were then compared with RC and RC_{PI} to determine their sensitivity to the view directions.

III. RESULTS

The results from the study are presented in radar charts in Fig.1 and 2 for each time point on rows and time of the year on columns. The values of DGP_c , GI, E_v , RC and RC_{PI} are shown for each of the 9 view directions. On each plot the windows orientation is specified (e.g. in Fig. 1 west is shown with W). Only the results from the two living rooms facing West and South are presented.

A. Living Room of Apartment 2 West-facing windows

Living room of apartment no. 2 located on the 5th floor of the building, is one of the investigated rooms. The apartment is West-East oriented and its area is 45 m². The living room has an area of 17 m² and its windows are facing west. The radar plots for the room in Fig. 1 show that RC_{PI} has the most sensitivity to view direction. The shape of the RC_{PI} plot is never symmetrical in relation to the window, unlike the plots of other parameters for several particular dates. The values of RC_{PI} , however, are higher in case of camera view direction 2 and 3 – to the right from the window in most cases, meaning that the relative contrast is much higher when looking to these directions. This is due to the relatively high brightness of the window in relation to the rest of the room and the location of the window in the FOV.

The graphs also show that the Ev values are symmetrical in relation to the window, with the highest illuminance directly in front of the window, gradually decreasing towards the back of the room. The GI plots show the same trend, however with lower values. In all graphs DGP_c and E_v are almost overlapping. Despite the season of the year, the plots for all metrics have repetitive shapes for the morning hours. This is due to lack of direct sunlight in the West-facing room. It can also be observed in Fig. 1 that in the equinox days all parameters' values show similar trends both at 4 and 6 p.m., which is due to a similar angle of the sun in these days. Also on solstice day June 21. at 4 p.m. the Ev plot is similar for 7 and 9 p.m., whereas the RC and RC_{PI} plots show different view-direction dependent tendencies in the afternoon than in the morning. The same can be seen for December 22. – the plot of Ev at 4 p.m. has similar shape to the plots for 7 and 9 a.m., while the shape of RC and RC_{PI} plots change for different periods of the day, indicating that strongest contrast in the afternoon is detected for different view directions compared to the morning.

B. Living Room of Apartment 8; South-facing windows

The visual comfort parameters values were also calculated for living room of apartment no. 8 and the radar plots for the room can be seen in Fig. 2. This North-South oriented apartment is located on the 5th floor and has an area of approx. 44 m². The living room has an area of approx. 17 m² and is oriented towards south. An overview of plots shows that the morning and afternoon hours of solstice and equinox days for both DGP_c components – Ev and GI, are less sensitive to the view direction than the RC and RC_{PI} parameters. The values of E_v and GI do not show large variations for different view directions, thus the plots have regular shapes and in most cases the highest discomfort glare was only detected in the direction towards the window.

Similar to the previous results, RC and RC_{PI} indicate considerably higher view direction dependency of the parameters' values. Another interesting observation is that when there is no direct sunlight expected in the rooms, e.g. 7 a.m. and 18 a.m., the shapes of the RC and RC_{PI} plots are similar for all the solstice and equinox days. Both parameters values are lowest for the view direction towards the back of the room. RC contrast is slightly higher towards the left side from the window, whereas the RC_{PI} values are highest for the view directions towards the right side of the window. At 9 a.m. and 4 p.m. (both closer to midday, when the angle of solar radiation is highest) the shapes of both RC and RC_{PI} plots vary distinctively for different solstice and equinox days.

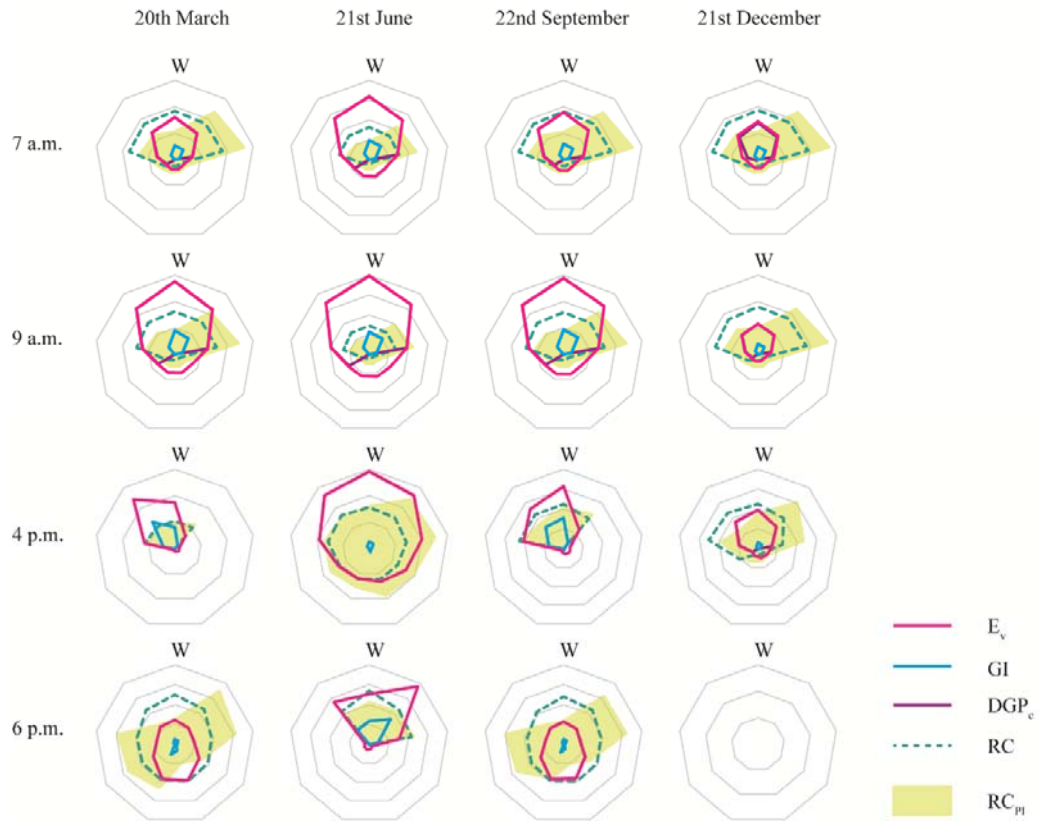


Figure 1 Radar plots of visual comfort parameters in solstice and equinox days at four specific hours during the occupancy in the living room of apartment no.2 (W – west, the window orientation)

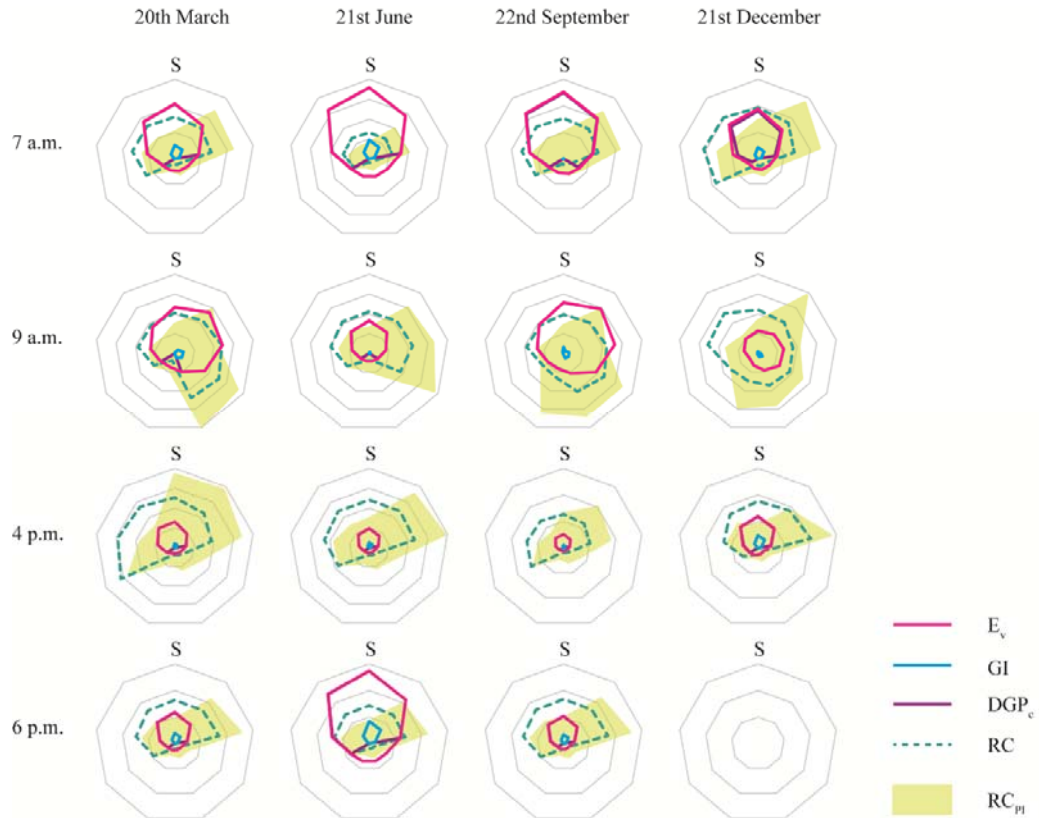


Figure 2 Radar plots of visual comfort parameters in solstice and equinox days at four specific hours during the occupancy in the living room of apartment no.8 (S – south, the window orientation)

IV. CONCLUSIONS

The results from the simulation-based study on visual comfort assessments in the typical residential building with heritage value in central Copenhagen are shown. This type of building has a façade typology that does not allow for sufficient daylight penetration over the year. Moreover, relatively dark interior spaces compared to the bright window surfaces could lead to visually uncomfortable conditions. This is, however, a subjective assessment and the same condition can be rated as cozy and appreciated in such building.

The results of the present study show that such conditions of high contrast can not be detected by the existing commonly used metrics for visual comfort assessments such as DGP. In cases with low illuminance levels, the DGP model only shows sensitivity when there is a direct and reflected sunlight in the FOV. The reason is that the dominant component of DGP is E_v , whereas the GI (Glare Impact), that stands for the illuminance contrast has less contribution to the overall result of the DGP index.

In this study a newly developed relative contrast model RC_{PI} is presented as a new approach for visual comfort assessment based on contrast. It allows detecting and quantifying contrast in the room, despite the presence of direct or reflected sunlight in the FOV or lack of it. RC_{PI} values vary distinctively for different view directions in relation to a window, unlike the values of DGP and its components that are mostly showing sensitivity towards the window.

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